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THE EFFECT OF MULTIBURST NO PRODUCTION ON ELECTRON DENSITIES AND HF ATTENUATION AT 60 KM ALTITUDE

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The effect of large scale production of NO due to a large number of nuclear bursts on the steady state electron densities at 60 km altitude was investigated. It was found, for ionization rates of 16 and 1600 ion-pairs/cm^3-sec, that the electron densities decreased significantly below that expected for ambient conditions for NO concentrations greater than 10^9 cm^{-3}. Since this is the region of maximum HF attenuation, the effects of multiburst NO production on HF communication systems could also be significant. Further calculations are planned.

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INTRODUCTION

There has, in the past, been a great deal of work concerning the degradation of HF communications systems following a nuclear burst. The long-term effects of a large number of bursts in the atmosphere has not, however, been studied very extensively. This report deals with an initial study of the effects of a large number of bursts on the chemistry of the atmosphere pertaining to HF attenuation in regions where the total integrated energy deposition is large but not large enough to cause large scale hydrodynamic effects.

The attenuation of HF signals is usually centered in an altitude region around 60 km, and our initial studies were conducted at this altitude during daytime. At this altitude, and for ionization rates of interest, the electron production rate is dominated by, except at early times, electron detachment from negative ions rather than by the direct ionization caused by gamma or beta ray deposition. This detachment is accomplished primarily by chemical detachment of O_2^- and O^- by atomic oxygen, the excited species $O_2(^1\Delta)$ and, to some extent, nitric oxide. The reactions involved are

$$O_2(^1\Delta) + O_2^- \rightarrow O_2 + O_2 + e \tag{1}$$

$$O + O_2^- \rightarrow O_3 + e \tag{2}$$

$$O_2(^1\Delta) + O^- \rightarrow O_3 + e \tag{3}$$

$$O + O^- \rightarrow O_2 + e \tag{4}$$

$$NO + O^- \rightarrow NO_2 + e \tag{5}$$
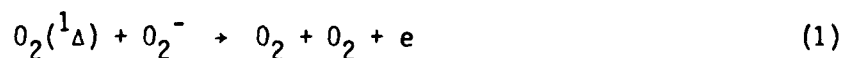
Photodetachment of all negative ions can also play a role.

$$X^- + h\nu \rightarrow X + e \tag{6}$$

In the ambient or near-ambient atmosphere at 60 km, reactions 1 to 4 provide virtually all the detachment with reactions 1 and 2 being dominant.

Any multiburst effect, then, which can signficiantly alter the concentrations of O, $O_2(^1\Delta)$, O_2^- or O^- could have significant effect on the electron density and therefore on HF propagation.

ODD OXYGEN CONCENTRATION

Under ambient conditions, the concentration of "odd oxygen," which we take as the sum of atomic oxygen and ozone, is determined by the photodissociation of O_2 and the various loss mechanisms. The processes which convert O to O_3 and back, such as

$$O_3 + h\nu \rightarrow O_2(^1\Delta) + O(^1D) \tag{7}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{8}$$

do not affect the odd oxygen total. One of the reaction cycles which depletes the odd oxygen involves NO,

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{9}$$

$$O + NO + M \rightarrow NO_2 + M \tag{10}$$

$$O + NO_2 \rightarrow NO + O_2 \tag{11}$$

Another reaction cycle involves species containing hydrogen and contains the reactions

$$H + O_3 \rightarrow OH + O_2 \tag{12}$$

$$OH + O_3 \rightarrow HO_2 + O_2 \tag{13}$$

$$O + HO_2 \rightarrow OH + O_2 \tag{14}$$

$$O + OH \rightarrow O_2 + H \tag{15}$$

$$O(^1D) + H_2O \rightarrow OH + OH \tag{16}$$

$$H_2O + h\nu \rightarrow OH + H \tag{17}$$

$$H + O_2 + M \rightarrow HO_2 + M \tag{18}$$

$$OH + HO_2 \rightarrow H_2O + O_2 \tag{19}$$

$$HO_2 + HO_2 \rightarrow H_2O_2 + O_2 \tag{20}$$

$$OH + H_2O_2 \rightarrow H_2O + HO_2 \tag{21}$$
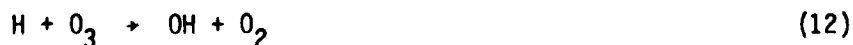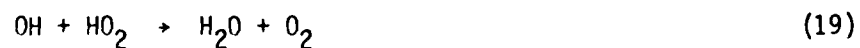
Reactions 20 and 21 are less important than the other reactions. The nitrogen and hydrogen cycles are not totally independent. The reaction

$$NO + HO_2 \rightarrow NO_2 + OH , \tag{22}$$

for instance, causes them to be somewhat interrelated.

In addition, the reaction

$$O + O_3 \rightarrow O_2 + O_2 \qquad\qquad (23)$$

destroys odd oxygen, but this reaction is never dominant.

Other cycles, such as one involving hydrocarbons, probably exist, but in the ambient 60 km altitude atmosphere the cycle involving H, OH and HO_2 (reactions 12 to 21) is the dominant one and virtually determines the odd oxygen content. Reactions 7 and 8 primarily determine the ratio of O to O_3 and reaction 7, together with the quenching reaction

$$O_2(^1\Delta) + O_2 \rightarrow O_2 + O_2 \qquad\qquad (24)$$

determines the $O_2(^1\Delta)$ concentration.

The main long-term effect on the atmosphere produced by nuclear bursts is the production and persistence of NO and NO_2. Unlike the other species formed by a nuclear burst, which react chemically to reform the molecules from which they were produced, NO and NO_2 persist in the atmosphere until diffusion and precipitation remove them. This occurs on a longer time scale than we are concerned with for HF communications problems. The presence of nuclear produced NO and NO_2 prevents the odd oxygen and $O_2(^1\Delta)$ concentrations from returning to their pre-burst values. As the NO increases (photochemical equilibrium keeps the NO_2 in a fixed ratio with the NO), reactions 9 to 11 become more important. At a concentration of NO of about 2×10^{10} cm^{-3} (ambient NO density is of the order of 10^8 cm^{-3}), the odd oxygen due to NO and NO_2 is about equal to the depletion due to H, OH and

HO_2. Any further increase in the NO concentration will produce signifi-
cant decreases in the odd oxygen concentration and, because of reaction 7,
in the $O_2(^1\Delta)$ concentration. This reduction of O and $O_2(^1\Delta)$ will
significantly reduce the detachment and therefore the electron density at
late times below that which would be expected using normal ambient NO
densities. This applies not only to the natural source of ionization but
to any nuclear burst which is detonated late in the barrage or some time
after the main barrage.

NEGATIVE ION DISTRIBUTIONS

Another way by which the NO produced by a nuclear burst affects the detachment and electron densities is via the distribution of negative ions. The negative ions which are formed initially are O_2^- and O^-. The reactions involved are

$$O_2 + e + M \rightarrow O_2^- + M \tag{25}$$

$$O_3 + e \rightarrow O^- + O_2 \tag{26}$$

$$O_2^- + O \rightarrow O^- + O_2 \tag{27}$$

These are the ions which are easily detached chemically (see reaction 1 to 5) and by photodetachment by sunlight. They also enter into a series of reactions with other atmospheric species to form other negative ions which are not easily detachable. These ions include O_3^-, O_4^-, CO_3^-, CO_4^-, NO_2^-, and NO_3^-. A simplified representation is shown in Figure 1. We see that the transformation of O^- and O_2^- to the terminal ions NO_2^- and NO_3^- (ions which cannot easily be chemically detached) takes place through a set of intermediate ions. These ions, O_3^-, O_4^-, CO_3^-, and CO_4^-, can either be transformed to the terminal ions by reactions with NO and NO_2 or back to the initial ions by reactions with O and O_3. Some of the important reactions are

$$O^- + O_2 + M \rightarrow O_3^- + M \tag{28}$$
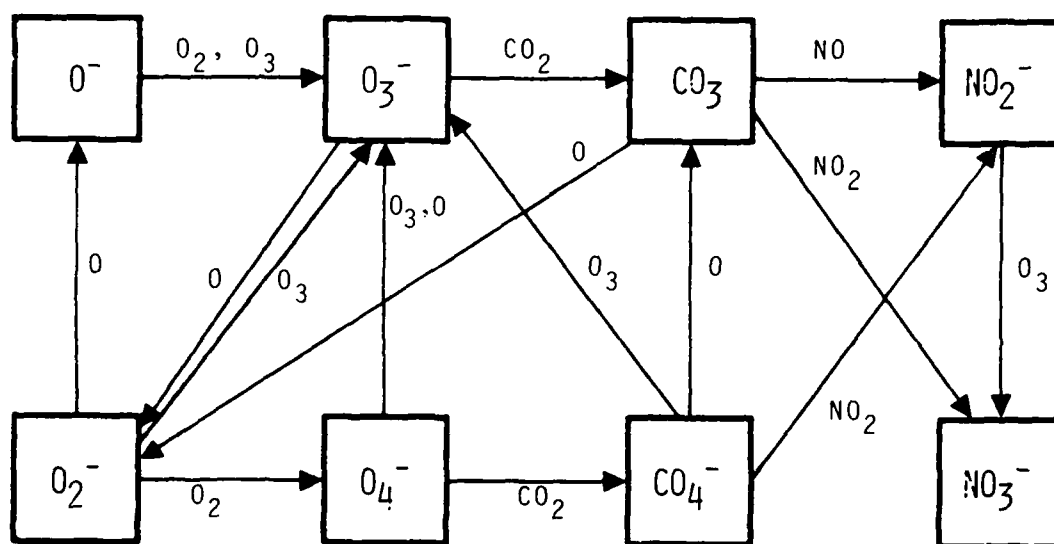
Figure 1.   Simplified negative ion chemistry scheme.

$$O^- + O_3 \rightarrow O_3^- + O \qquad (29)$$

$$O_2^- + O_2 + M \rightarrow O_4^- + M \qquad (30)$$

$$O_4^- + CO_2 \rightarrow CO_4^- + O_2 \qquad (31)$$

$$CO_4^- + O \rightarrow CO_3^- + O_2 \qquad (32)$$

$$O_3^- + CO_2 \rightarrow CO_3^- + O_2 \qquad (33)$$

$$O_4^- + O_3 \rightarrow O_3^- + O_2 + O_2 \qquad (34)$$

$$CO_3^- + NO \rightarrow NO_2^- + CO_2 \qquad (35)$$

$$CO_3^- + NO_2 \rightarrow NO_3^- + CO_2 \qquad (36)$$

$$CO_4^- + NO_2 \rightarrow NO_2^- + CO_2 + O_2 \qquad (37)$$

$$O_4^- + O \rightarrow O_3^- + O_2 \qquad (38)$$

$$CO_4^- + O_3 \rightarrow O_3^- + CO_2 + O_2 \qquad (39)$$

$$CO_3^- + O \rightarrow O_2^- + CO_2 \qquad (40)$$

$$O_3^- + O \rightarrow O_2^- + O_2 \tag{41}$$
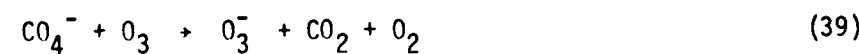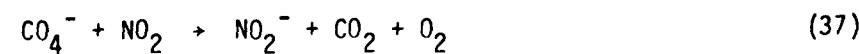
If the NO and NO_2 concentrations are greatly increased, the formation rate of NO_2^- and NO_3^- from the intermediate ions is also greatly increased (see reactions 35, 36, and 37). If the O is decreased, the formation rate of O_2^- from O_3^- and CO_3^- (see reactions 40 and 41 is decreased. This not only results in a more rapid evolution of NO_2^- and NO_3^- but smaller steady state concentrations of O_2^- and O^-. Referring to reactions 1 and 5, we see that this will also result in a decrease in the electron detachment and steady state electron density.

NO PRODUCTION BY NUCLEAR BURSTS

NO is produced both in the high temperature fireball and in regions outside the fireball where energy is deposited by X-rays, neutrons, beta rays, and gamma rays. Low altitude bursts produce little or no nitric oxide at 60 km unless the bursts are at altitudes such that the fireballs rise and stabilize around that altitude. High altitude bursts deposit most of their energy outside of the fireball, and a significant fraction of this energy can be deposited around 60 km, particularly by X-rays.

The amount of NO per ion-pair evolved by the energy deposition is a variable which depends on the amount of NO present already. This is primarily because of the different ways in which $N(^2D)$ and $N(^4S)$, which are formed very rapidly during the energy degradation processes following the deposition of energy, interact with NO and the atmospheric species. Both react with O_2 to form NO by the reactions

$$N(^2D) + O_2 \rightarrow NO + O \tag{42}$$

$$N(^4S) + O_2 \rightarrow NO + O \tag{43}$$

Reaction 42 is rapid and is almost six orders of magnitude faster than reaction 43 at 60 km altitude.[1] Thus, virutally all the $N(^2D)$ produced initially reacts to form NO. The fate of the ground state nitrogen, $N(^4S)$, can be quite different. When the NO concentration is larger than about 4×10^8 cm^{-3}, $N(^4S)$ will primarily react with NO in the following manner:

$$N(^4S) + NO \rightarrow N_2 + O \tag{44}$$

Thus, any $N(^4S)$ atom which enters into reaction 44 not only does not form an NO molecule but destroys one which has already been formed by another nitrogen atom. When the NO concentration is large, further NO production is highly dependent on the difference between the amount of $N(^2D)$ and $N(^4S)$ produced initially. Since the amounts of $N(^2D)$ and $N(^4S)$ formed are not too different (0.68 and 0.46 per ion-pair in our calculations), a moderate uncertainty in either of these numbers causes a large uncertainty in the difference.

The values obtained in our calculations for the NO per ion-pair produced are shown in Table 1.

Table 1. NO production per ion-pair.

Total Ion-Pair Production	NO per Ion-Pair
10^8	1.2
10^9	0.67
10^{10}	0.40
10^{11}	0.33
10^{12}	0.30

These values were obtained for the total ion-pairs produced instantaneously at t = 0. If the ioinization were spread in time, the values for the NO produced would be somewhat larger.

ELECTRON DENSITY REDUCTION DUE TO NO

The results of our calculations for the steady state electron densities as a function of NO concentration are shown in Figure 2. The upper curve is for an ionization rate, q, of 1.6×10^3, and the lower curve is for $q = 1.6 \times 10^1$ ion-pairs/cm^3-sec. The smaller q is representative of the ionization rate at 60 km altitude which can be found 1000 km away from a high altitude megaton fission yield burst after about three hours.[2] The larger q is representative of the ionization rate in the beta patch after about three hours for a similar burst.[2]

The lower curve is more typical of what we might expect over a large region of space several hours after a high altitude nuclear burst. We see that as the NO concentration increases over the ambient value, which is of the order of 10^8 cm^{-3}, the steady state electron density decreases significantly, particularly for NO concentrations above 10^9 cm^{-3}. At a value of the NO concentration of about 4×10^{10} cm^{-3}, the electron density is decreased a factor of ten. This would correspond to an integrated ionization of approximately 10^{11} ion-pairs (see Table 1). At this point, the odd oxygen and $O_2(^1\Delta)$ is about a factor of two less than ambient. The decrease in the O_2^- and O^- is about a factor of nine. This causes a factor of eighteen decrease in the detachment of O_2^- and O^- by O and $O_2(^1\Delta)$. The reason that the electron density has only decreased a factor of ten is due to the fact that the detachment due to other processes is now a significant part of the total detachment. In particular, the reactions

$$NO_2^- + h\nu \rightarrow NO_2 + e \tag{45}$$

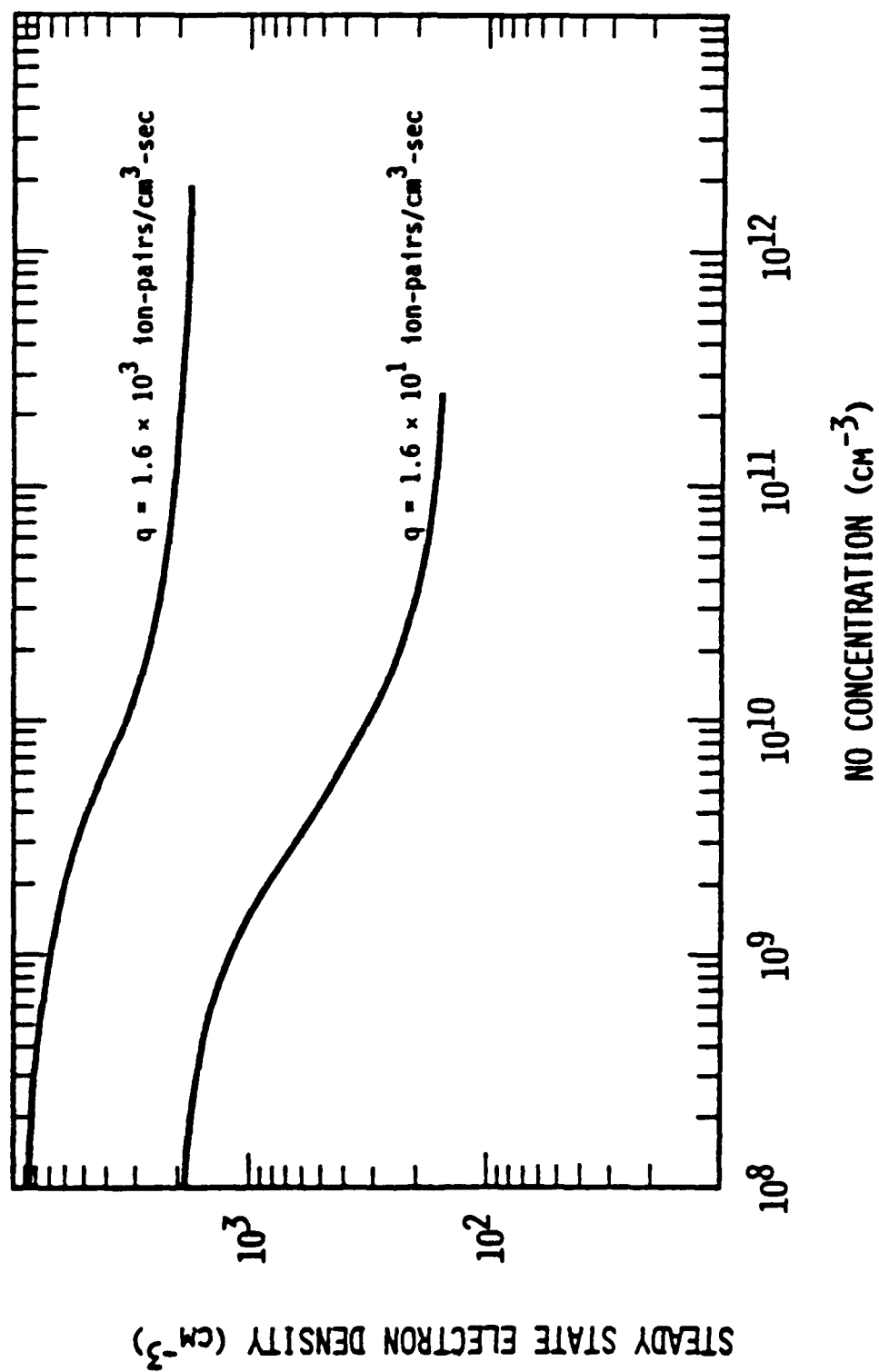$$NO + O^- \rightarrow NO_2 + e \tag{46}$$

have increased signficantly.

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Figure 2. Steady state electron density versus NO concentration.

As the NO concentration is increased to values above 4×10^{10} cm^{-3}, the electron density levels off at a fairly constant value. We are in a region now where reaction 45 is the dominant detachment mechanism and any further decrease in the detachment of O_2^- and O^- does not signfiicantly affect the electron density.

A recent change in one of the rate coefficients used in our calculations will probably make the electron density in future calculations decrease even further than shown in Figure 2 for large NO concentrations. The rate coefficient is for the reaction

$$NO_2^- + O_3 \rightarrow NO_3^- + O_2 \tag{47}$$

and the value we have used is 1.8×10^{-11} cm^3/sec. A better value is 1.2×10^{-10} cm^3/sec.[3] Use of the larger coefficient will decrease the amount of NO_2^- and increase the NO_3^-. Since NO_3^- has a smaller sunlight photodetachment rate than NO_2^-, detachment from O_2^- and O^- will dominate to large NO concentrations and the electron density curve will decrease to lower values before leveling off.

The upper curve in Figure 2 shows the same qualitative behavior as the lower curve. The electron density, however, does not decrease as much and levels off at a higher relative value. The reason for this is not yet clear to us, but further calculations should clarify this behavior. As q is raised further than shown in Figure 2, we will reach a value such that q will dominate the electron production rather than detachment, and the increased NO concentration will have much less effect on the electron density than for lower q's. This, however, does not occur until q is of the order of 10^6 cm^{-3}-sec^{-1} or greater under normal conditions. This usually corresponds to early times after a burst and possibly before steady state ion distributions are established.

SPECIFICATION OF AMBIENT CONSTITUENTS

One of the problems we encountered in our calculations is that most specifications (e.g., the ROSCOE ambient atmosphere[4]) of the concentrations of the minor constituents for natural or ambient conditions are not consistent with the chemistry schemes in use. This means that when chemistry models are applied to the atmospheric minor species, the concentrations of these species will change even when no perturbation, such as a nuclear burst, is involved. If one is interested in phenomena near ambient conditions or the relaxation of the atmosphere to new ambient conditions after a strong disturbance, this is a serious deficiency.

At 60 km altitude during the day, most of the species concentrations in which we are interested are in photochemical equilibrium with certain other constituents. The concentrations of these other species, such as N, O, H_2O, CO_2, NO, H_2, and N_2O, are determined largely by transport processes. Since our chemistry code does not include these transport processes, these species concentrations must be specified initially. The remaining species concentrations must then be obtained by applying sunlight and the chemistry scheme for a sufficient time to establish a steady state. Though this was done for our present calculations, the updating of a number of reaction rates just prior to making our runs introduced some inconsistencies. In further calculations, a new ambient specification will be done whenever the chemistry scheme is changed.

A problem related to this is the specification of the water vapor concentration. The water vapor content in the atmosphere is variable and depends on, among other things, geographical location and time of the year. The amount of water vapor used impacts on both the odd hydrogen and odd oxygen species concentrations. We have used a nominal value of four parts per million for the H_2O concentration. In future calculations, different values between one and ten parts per million will be used to determine the importance of this specification.

CONCLUSIONS

The widespread production of nitric oxide by a number of nuclear bursts can have appreciable effect on the propagation of HF signals in the region of 60 km altitude, which is where HF attenuation is greatest. The NO accomplishs this through a reduction in the ambient atomic oxygen and $O_2(^1\Delta)$ concentrations and a reduction in the amount of O_2^- and O^- produced by a given ionization rate. This reduces the electron detachment and thus the electron density.

A large scale attack involving all surface bursts would not produce an appreciable amount of NO in the region of 60 km. However, a number of large yield bursts between 30 km and 300 km altitude could provide the requisite amount of NO through a combination of X-ray, beta ray, and gamma ray energy deposition and thermally produced fireball NO which is heaved to the region of 60 km altitude. These bursts could be the part of a ground attack in which salvage fusing was used or part of a high altitude attack on our UHF or ELF-VLF communications systems. In the case of a large scale ground attack, it is difficult to imagine any HF ray path not having to traverse regions containing fission debris unless the transmitter and receiver are airborne. In this case the HF degradation will probably be dominated by the attenuation in these regions and not in the region around 60 km altitude. In the case of a high altitude attack, however, the production of NO could decrease the expected attenuation effects in the D-region at late times and perhaps even enhance HF propagation.

Further calculations are planned over a range of altitudes covering 50 to 70 km and for q's of 0.1 to 10^5 ion-pairs/cm^3-sec. Calculations will also be made to specify ambient constituents which are consistent with the chemistry scheme being used. This will insure that the electron density decreases which are calculated, particularly near ambient, are truly due only to the effect of nitric oxide.

20

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